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Stress Corrosion Cracking Behavior of Oxide Dispersion Strengthened Ferritic Steel in Supercritical Pressurized Water

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Summary and Conclusions

The foremost consideration in the successful development and deployment of advanced nuclear reactor is the safety, performance and reliability of the systems. One of the critical issues for these requirements can be the soundness of structural materials, which endure high-temperature, high neutron doses and extremely corrosive environment. Therefore, oxide dispersion strengthened steels have been considered to be candidates for several advanced nuclear systems with higher thermal efficiency, because of their excellent performance as structural component in such a severe environments. However, the experimental data on the SCC susceptibility of “ODS steels” in supercritical pressurized water (SCPW) has not been reported to our knowledge. And all of the tests for SCC susceptibility in SCPW were conducted in SCPW dissolved with oxygen but not in SCPW dissolved with hydrogen.

In this research, the stress corrosion cracking susceptibility and fracture mode of ODS ferritic steel and conventional structural steels such as F82H ferritic/martensitic steel and SUS316L austenitic stainless steel in supercritical pressurized water (25 MPa, 500 °C) dissolved with various oxygen and hydrogen contents were investigated by means of steady strain rate tests (SSRT), which were performed at a higher strain rate of 1×10^{-3} s^{-1} and lower strain rates of 1×10^{-6} s^{-1} or 5×10^{-7} s^{-1}. The DO and DH contents of the water are DH = 0.4 ppm, DO and DH < 0.01 ppb and DO = 8 ppm. In addition, high temperature tensile test in vacuum was also performed at 500 °C to compare the deformation and fracture behavior with those of the corrosive environment of SCPW. And the specimen geometry effects on the SCC susceptibility and the deformation mechanism in vacuum of ODS steels were investigated by means of slow strain rate test (SSRT) in vacuum and SCPW. The following results are obtained:

1. SCC susceptibility and fracture mode of a 15Cr-4Al-2W ODS ferritic steel in SCPW with different water chemistry.

   (1) The deformation and fracture behavior of the ODS steel are independent of the test conditions, such as strain rate, environment namely vacuum or SCPW and DH/DO contents in SCPW. All the tested specimens shows a ductile fracture showing a cup and corn shape of fractured region.

   (2) The effect of DH and DO contents on the fracture behavior is negligible for the ODS steel.

(3) The high resolution EPMA observations revealed that oxide layer thickness depends on the DO/DH contents and the thickness of the Cr/Al complex oxide film is thickest for the specimen tested in DH=0.4 ppm. In other words, SCPW dissolved with extremely low oxygen contents interrupts the creation of the Cr/Al complex oxide layer and gives rise to thicker outer oxide layer in DH = 0.4 ppm and DO & DH < 0.01 ppm.

(4) The detailed EPMA and SEM analysis showed that small "corrosion layer cracking" was observed in the necking region of all the tested specimens except for that tested in vacuum at higher strain rate. The number of the oxide layer cracks was not influenced by the change in the strain rate ranging from 1×10^{-3} s^{-1} to 5×10^{-7} s^{-1}.

(5) The diffusion process of the ODS steel in SCPW follows grain boundary diffusion mechanism. Although grain boundary diffusion, which is faster than the bulk or effective diffusion, was mainly occurred, the thickness of oxide layers on the ODS steel is very thin and similar, regardless of the water chemistry. Therefore, it can be suggested that the grain boundary diffusion mechanism of the 15Cr-4Al ODS steel could be affected by nano-particles and presence of Al-Cr rich complex oxide layer.

(6) After the test in vacuum at a strain rate of 5×10^{-7} s^{-1}, the corrosion layer cracking was observed, indicating that the small amount of oxygen in the vacuum may cause corrosion and corrosion layer cracking in necking area.

(7) The 15Cr-ODS ferritic steel shows no susceptibility to SCC in SCPW in the test condition of this research.

2. The effect of SCPW chemistry on the SCC susceptibility of SUS316L and F82H.

(1) IG-SCC mainly occurred in SUS316L in the SCPW with dissolved hydrogen. On the other hand, the fracture mode at crack initiation stage in SCPW with dissolved oxygen was intermixed with intergranular and transgranular SCC.

(2) Although SUS316L exhibits SCC in SCPW with different water chemistry, the susceptibility to SCC was highest in the water with dissolved hydrogen concentration followed by that in the deaerated SCPW, while SCC was so limited in the water with dissolved oxygen.

(3) In contrast, F82H ferritic/martensitic steel is resistant to SCC in the SCPW dissolved with hydrogen and oxygen in this test condition, while it suffers from much severe oxidation. The surface cracks observed after the test were oxide layer crack limited to the corrosion products.

(4) The SCC of SUS316L in SCPW in this research can be explained by the combination of slip-dissolution model and film-induced cleavage model. The resistance to SCC of F82H

ferritic/martensitic steels was explained by crystalline structure of lattice: BCC lattice is less sensitive to SCC through the easiness of cross slip.

(5) It was predictable that the ODS ferritic steel shows better resistant against SCC than the other metallic materials because nano-size oxide particles can trap dislocations by pinning effect, very fine grain size prevents crack development and ferritic structure is also less sensitive to SCC.

3. The effect of specimen geometry and surface condition on the SCC susceptibility in SCPW

(1) In the case of austenitic stainless steel and ferritic/martensitic steel, the miniaturized specimen can give reliable deformation and fracture behavior information to the SCC susceptibility by means of SSRT.

(2) However, ODS steel needs careful consideration of miniaturization and surface finishing in order to evaluate the SCC susceptibility with using SSRT technic.

(3) Surface roughness or residual stress of ODS steel could be a factor to determine the SCC susceptibility to the SCPW.

4. Deformation mechanism in vacuum of the materials studied in this research as a reference of the experimental data for comparison between vacuum and SCPW.

(1) The result of SSRT in a vacuum at 773K with the different ODS steels (SOC-9, SOC-14, SOC-16) shows that the lower the strain rate, the lower the tensile strength. However, no material dependence was shown with the tested specimens.

(2) Tensile yield stress is remarkably dependent on the strain rate, showing a large increase with increasing strain rate, while tensile elongation is not remarkably influenced by strain rate.

(3) Reduction in area after SSRT in a vacuum at 773K was relatively constant, regardless of strain rate.

(4) According to the precise observations of fractured surface, there was no strain rate effect on the fracture mode, and only ductile fracture was observed for all the specimens tested in the study. This trend was independent of material.

(5) The *m* value in Eq. (2) for the ODS steels was 31 that is very large, implying that the deformation mechanism is related with thermally-activated dislocation motion and/or possibly grain boundary sliding.

The obtained main results of this study are summarized as follows:

1. Slow strain rate tests in supercritical pressurized water revealed that 15Cr-ODS ferritic steel did not show the susceptibility to SCC at all the test conditions in this study such as strain rate and water chemistry, indicating that all the tested specimens show a ductile fracture with a cup and corn shape of fracture region. Although cracks are observed in the necking region, the cracks do not affect the tensile properties of ODS ferritic steel because it was revealed, in this study, that the crack development mechanism of the ODS steel is the "corrosion layer cracking" of the very thin oxide film. Therefore, degradation of tensile properties of the ODS steel is only influenced by the thickness of oxide film in the researched water condition.

2. SUS316L austenitic stainless steel exhibits greater susceptibility for SCC than ODS ferritic steel and F82H ferritic/martensitic steel, while it shows good resistance to corrosion. However, SCC susceptibility of SUS316L shows complex behavior to the strain rate change and the different water chemistry. It indicates that water chemistry control is essential for the SUS316L to apply to supercritical water cooled system.

3. Although F82H ferritic/martensitic steel did not show any susceptibility to SCC in SCPW, it severely suffers from oxidation that is inadequately significant for practical applications.

4. Additionally, ODS steel needs careful consideration on the specimen size effect and surface finishing condition in order to evaluate the SCC susceptibility by means of SSRT.

In conclusion, ODS ferritic steel shows no susceptibility to SCC in SCPW and the steel has noticeable feasibility as structural material for application to SCPW cooled nuclear systems, such as SCPW reactor, fusion blanket and also high burn-up light water reactors, where high corrosion resistance and high-temperature strength are simultaneously required.